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Using High-Resolution, Regional-Scale Data to Characterize Floating Aquatic Nuisance Vegetation in Coastal Louisiana Navigation Channels

by Yvonne C. Allen and Glenn M. Suir

INTRODUCTION

Aquatic vegetation control. Traditionally, the US Army Corps of Engineers (USACE) New Orleans District (MVN) has relied on a team of three highly trained field personnel to monitor and determine the appropriate location and treatment frequency for floating nuisance aquatic vegetation (AV) within their area of responsibility (AOR) in coastal Louisiana (Figure 1). Recently, the MVN has experienced a reduction in funding under the Removal of Aquatic Growth (RAG) Program. As a result of decreased funding, infestations have not been routinely monitored and normal control operations have not been performed. While concern about infestations is increasing, assessment and management remain insufficient, resulting in a high potential for impeded navigation on waterways in the district. In the absence of an active RAG program, the USACE Engineer Research and Development Center (in coordination with MVN) investigated the effectiveness of remote sensing to evaluate and track the growth of nuisance aquatic vegetation.

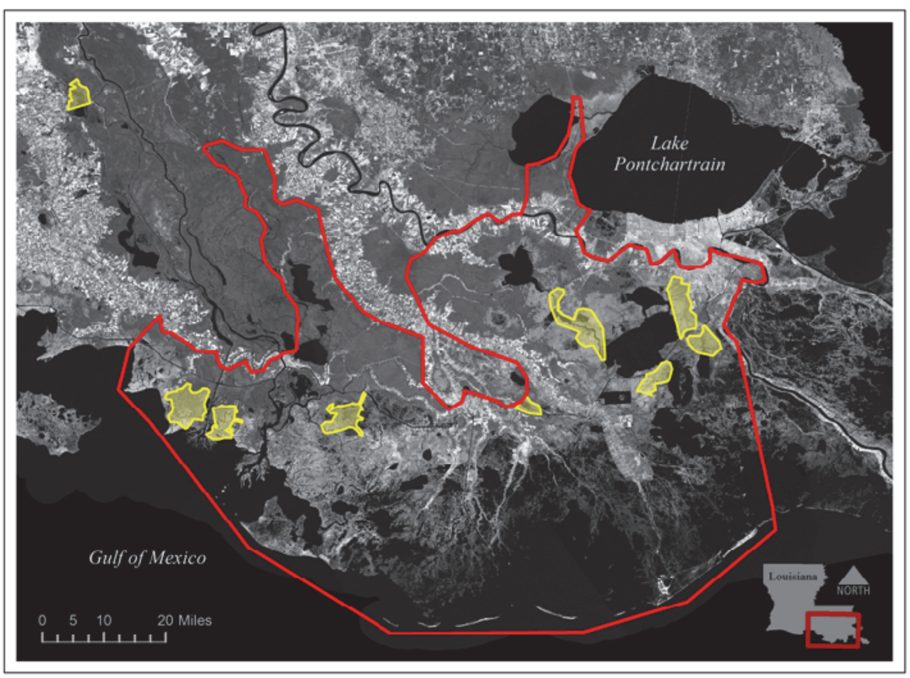

Figure 1. MVN area of responsibility (red) for control of nuisance aquatic vegetation. "Hotspot" areas identified by the MVN field crews are outlined in yellow.

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Previous studies have demonstrated the ability of multi-spectral imagery and remote sensing techniques to identify and quantify seasonal and yearly changes in aquatic vegetation type and distribution in inland waters with suitable field data for image calibration (Jensen et al. 1992, Steeves et al. 1999). These remote sensing methods are increasingly important to RAG programs because they: (1) reduce the time and resources required for mapping aquatic plant infestations in navigable waterways and identify potential threats to water management structures, which facilitates more frequent updates of potentially rapidly changing conditions; (2) provide presence/absence information that is critical for the planning, monitoring, and effectiveness of vegetation removal efforts (Jakubauskas et al. 2002); and (3) provide capabilities for predicting future aquatic plant infestations and identifying areas of concern. The objective of this study was to develop an innovative capability to regularly and rapidly generate high-resolution, regional-scale mapping products that characterize the presence of floating aquatic nuisance vegetation in USACE district navigation channels. This will enhance the district's effectiveness and efficiency in removal of aquatic plant growth. This project used and evaluated several remote sensing platforms to determine the optimal combination of spatial and spectral resolution that may be used to achieve the goals of a traditional RAG monitoring program.

METHODS

Sensors

Moderate resolution. Three moderate spatial resolution sensors (Landsat 7, SPOT 4, and SPOT 5) were evaluated in this study. The Landsat 7 satellite (SLC-off, see details below) was the primary source of imagery used in the analysis of AV conditions in coastal Louisiana. Landsat 7 imagery is freely available from the US Geological Survey (USGS) through EarthExplorer or GloVis websites. The revisit frequency over the same orbital path is 16 days, but there is an overlap of approximately 55 km between paths, increasing the revisit frequency for areas that fall within that overlap (Figure 2). Landsat is a moderate-resolution sensor (Table 1) that covers a large spatial extent and captures six bands of multispectral information, but the spatial resolution may be less effective for resolving details of AV condition in narrow waterways.

In 2009, USGS, in partnership with the National Aeronautics and Space Administration and the US Department of Agriculture, contracted with SPOT Imaging Corporation to receive SPOT 4 and 5 imagery products. The North American Data Buy (NADB) Program was initiated to provide USGS and their partner agencies with imagery that may be used to determine land cover information in the event of a failure in Landsat satellites. SPOT imagery, obtained through the NADB program, is available at no cost to US federal civil agencies, tribal governments, and US state and local governments. The coverage goal of this program is to provide monthly, cloud-free coverage over much of the continental United States (CONUS) and parts of Canada and Mexico. At 60 km, the SPOT scene footprint is smaller than Landsat (Figure 2), taking three paths and seven scenes to cover the same MVN AOR that is covered with two Landsat scenes. The spatial resolution of SPOT 4 is similar to Landsat, but SPOT 5 provides an appreciably higher spatial resolution (Table 1). The spectral information for both SPOT sensors is limited to four bands in the visible and near infrared portion of the electromagnetic spectrum.

High resolution. Higher resolution imagery from four sensors (WorldView, Quickbird, GeoEye, and IKONOS) was also evaluated. Imagery from these sensors (Table 1) is available to the USACE through the Geospatial Information and Services policy guidance (Army Regulation 115-11; US

Department of the Army 2001). The Army Geospatial Center (AGC) Imagery Office serves as the Army's Executive Agent for commercial imagery and has an agreement with the National Geospatial-Intelligence Agency (NGA), allowing for the acquisition of archived, unclassified imagery at no cost to the services and intelligence communities. The NGA awards contracts to high-resolution commercial data providers, allowing free use of these data to USACE personnel. These sensors can be "tasked," meaning that users can request that the AGC acquire new data in designated locations; however, other high-priority requests or concerns may override civil priorities.

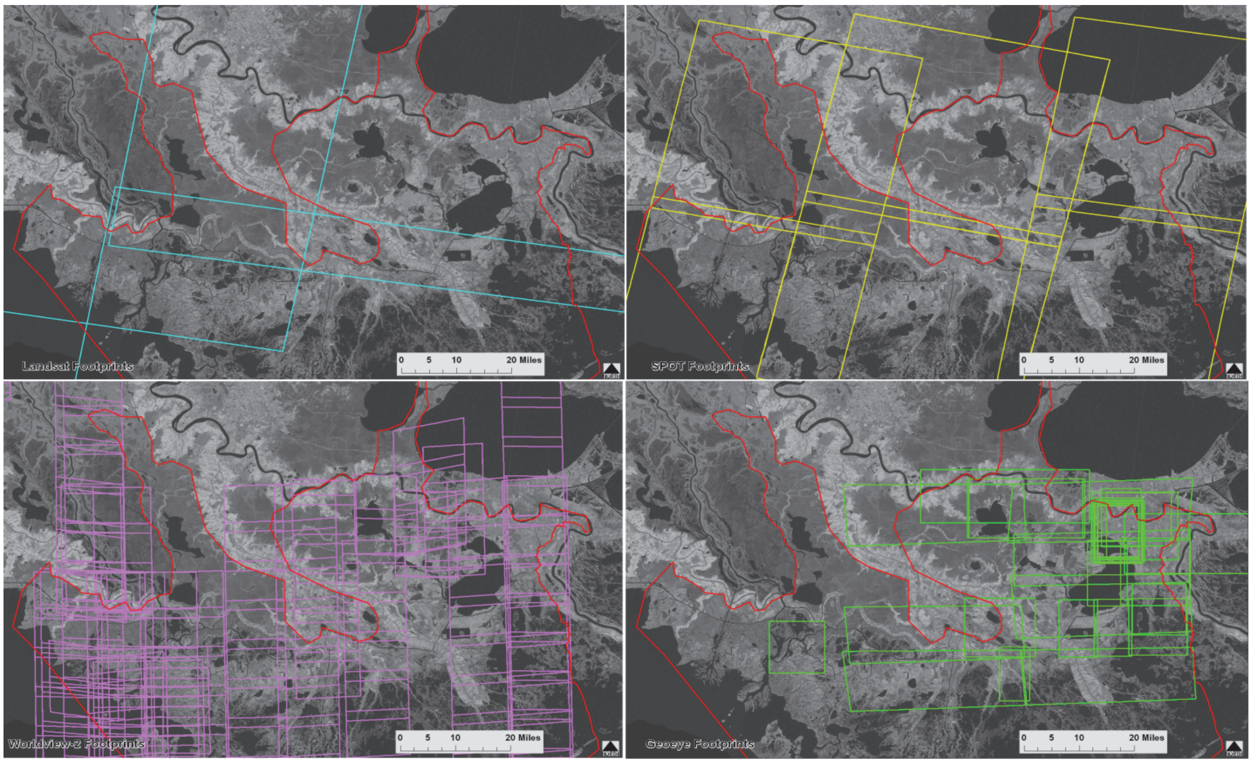

Figure 2. Comparison of footprints from various image sensors used in this study. Landsat (blue) is in the upper left panel, SPOT (yellow) is in the upper right panel, WorldView-2 (WV-2; purple) is in the lower left panel, and GeoEye (green) is in the lower right panel. Note that the footprints for WV-2 and GeoEye are largely based on historically acquired imagery, not imagery that was acquired for this project. The New Orleans District (MVN) area of responsibility (AOR) for control of nuisance aquatic vegetation in coastal Louisiana is outlined in red.

Table 1. Technical specifications for remote sensing platforms evaluated in this study.

Satellite/Sensor	Spectral Bands	Spatial Resolution (m) Pan	Spatial Resolution (m) Multispectral	Swath Width (km)	Repeat Orbit (days)	Taskable	Availability
Landsat 7 ETM+	6 multispectral + pan + thermal	15	30	183	16	N	Free
Landsat 8 * (*Feb 2013*)	6 multispectral + pan + thermal	15	30	185	16	N	Free
SPOT Imaging SPOT 4	4 multispectral + pan	10	20	60	2-3	Y	USGS NADB
SPOT Imaging SPOT 5	4 multispectral + pan	2.5 or 5	10	60	2-3	Y	USGS NADB

SPOT Imaging SPOT 6	4 multispectral + pan	1.5 or 5	6	60	2-3	Y	cost
Digital Globe WorldView-2	8 multispectral + pan	0.46	1.8	16.4	1	Y	cost / AGC
Digital Globe Quickbird	4 multispectral + pan	0.65	2.6	18	2.5	Y	cost / AGC
GeoEye GeoEye-1	4 multispectral + pan	0.41	1.6	15.2	<3	Y	cost / AGC
GeoEye IKONOS	4 multispectral + pan	0.82	3.2	11.3	~3	Y	cost / AGC

The mode of acquisition and spatial footprint for each of the high-resolution sensors varies (Figure 2). WorldView-2 (WV-2) and IKONOS acquire imagery in north-south strips whose length is specified by the project requirements. GeoEye imagery is acquired in east-west strips. Acquisition of adjacent strips may also be requested to increase areal coverage. With the single exception of WV-2 (eight spectral bands), the higher resolution sensors evaluated as part of this study are limited to four spectral bands.

Moderate resolution processing. ArcGIS [Environmental Systems Research Institute (ESRI), Redlands, California] was the primary software used to assess imagery products. Single-band Landsat 7 imagery was loaded into ESRI's mosaic dataset format, which provides on-the-fly mosaicing, layer stacking, and pan-sharpening. SPOT data were loaded as individual geotifs and pan-sharpened as required.

Many locations within the MVN AOR contain physical blocks to navigation, such as gates, drill stems, and earthen dams. The entire AOR was mapped for these structures using the most recently available high-resolution aerial imagery (USGS 2008; and National Agriculture Imagery Program 2009 and 2010). High-density AV blockages that occurred within a section of waterway or canal that was physically blocked to navigation were not typically included in the regular AV evaluations, since these locations would not normally be subject to AV control measures.

A 10- by 10-km search grid was established to assist in a systematic visual evaluation of each image. Within the MVN AOR, each image was examined for locations that were completely blocked to navigation by high densities of AV. These locations were coded as "severe." An example of a waterway that is completely blocked to navigation by water hyacinth (*Eichhornia crassipes*) is shown in Figure 3. Where imagery showed no occurrence of AV, locations were coded as “clear.” All locations not satisfying the “severe” (complete blockage) or “clear” (no presence of AV) criteria were coded as “moderate.” An example of a “moderate” site, defined as containing any combination of water and AV pixels, is shown in Figure 4. If a location could not be evaluated due to cloud or sensor coverage issues, it was coded as "did not evaluate" (DNE).

Figure 5 is an example of the imagery and coding scheme results. As new blocked locations were discovered in the imagery, previous images were examined to confirm the historical status of that location. Monthly updates were provided to MVN detailing the location and severity of AV distributions based primarily on results from Landsat imagery, and when available, corroborated with field notes/photography or higher resolution imagery. Results were provided in Google Earth file format and as pdf maps. A USACE intraweb map interface was also developed showing the location and status of blockages with an interactive time slider (*http://tabitha.erd.ds.usace.army.mil/GDAF/Atchafalaya/map.html*, Figure 6).

Figure 3. Example of a waterway that is completely blocked to navigation by water hyacinth and would be classified as "severe" in this study.

Figure 4. Example of a waterway that is densely covered with hyacinth, and would be classified as "moderate" in this study.

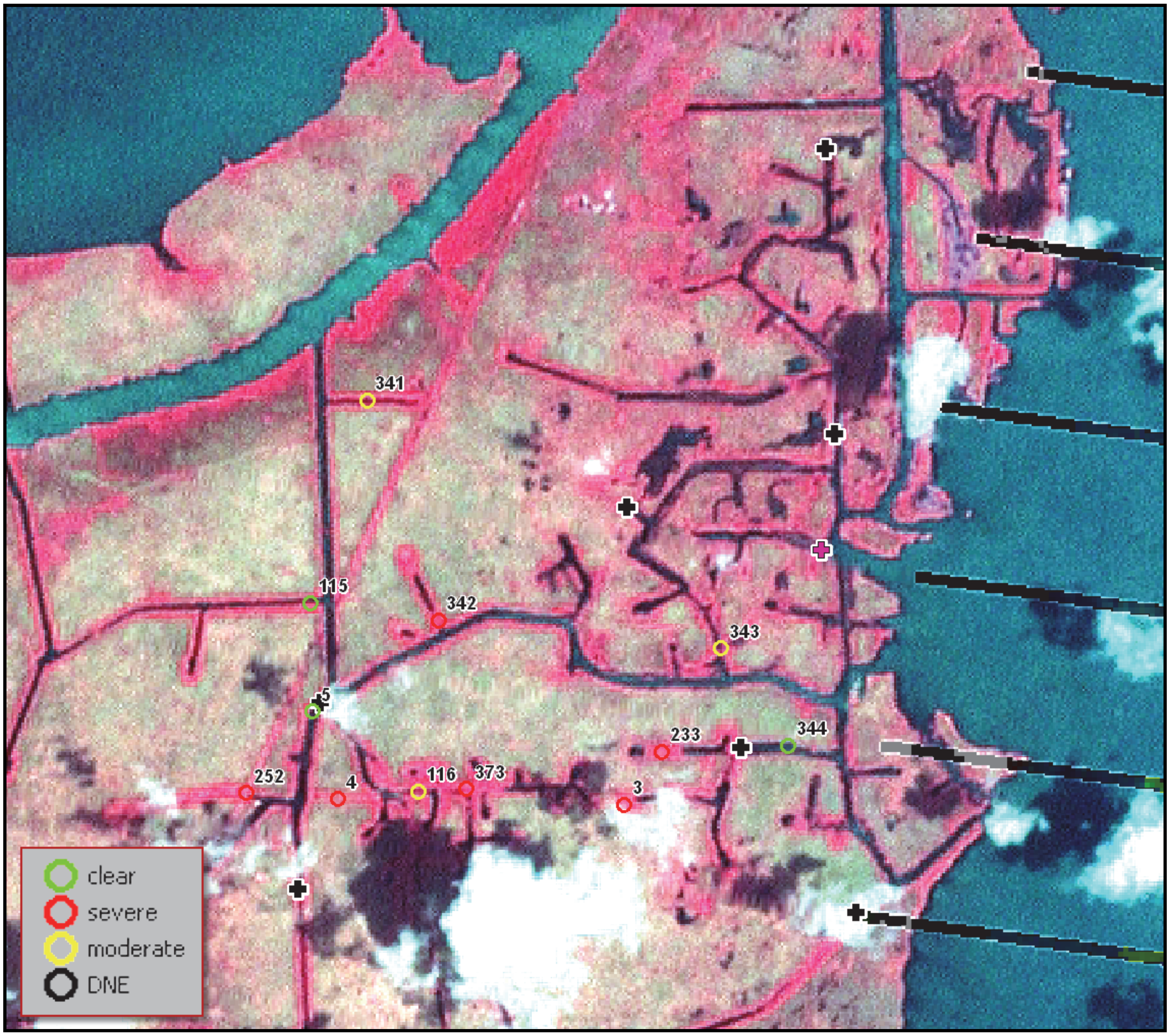

Figure 5. Typical Landsat 7 scene (1 August 2012). Location and severity of AV blockages are noted with circles. Physical blocks to navigation are indicated with crosses.

RESULTS

Observations and seasonal trends. During the summer of 2012, the presence or absence of water flow had a strong influence on the likelihood of AV populations. The earliest and most dense populations of AV were found in areas that typically receive little to no flow, such as oil and gas location (dead-end) canals. Waterways in the MVN AOR that were less than 100 m in width were subject to severe blockage from AV. Unobstructed waterways greater than 100 m may have experienced some narrowing due to fringing AV populations, but they were never completely blocked during the summer of 2012.

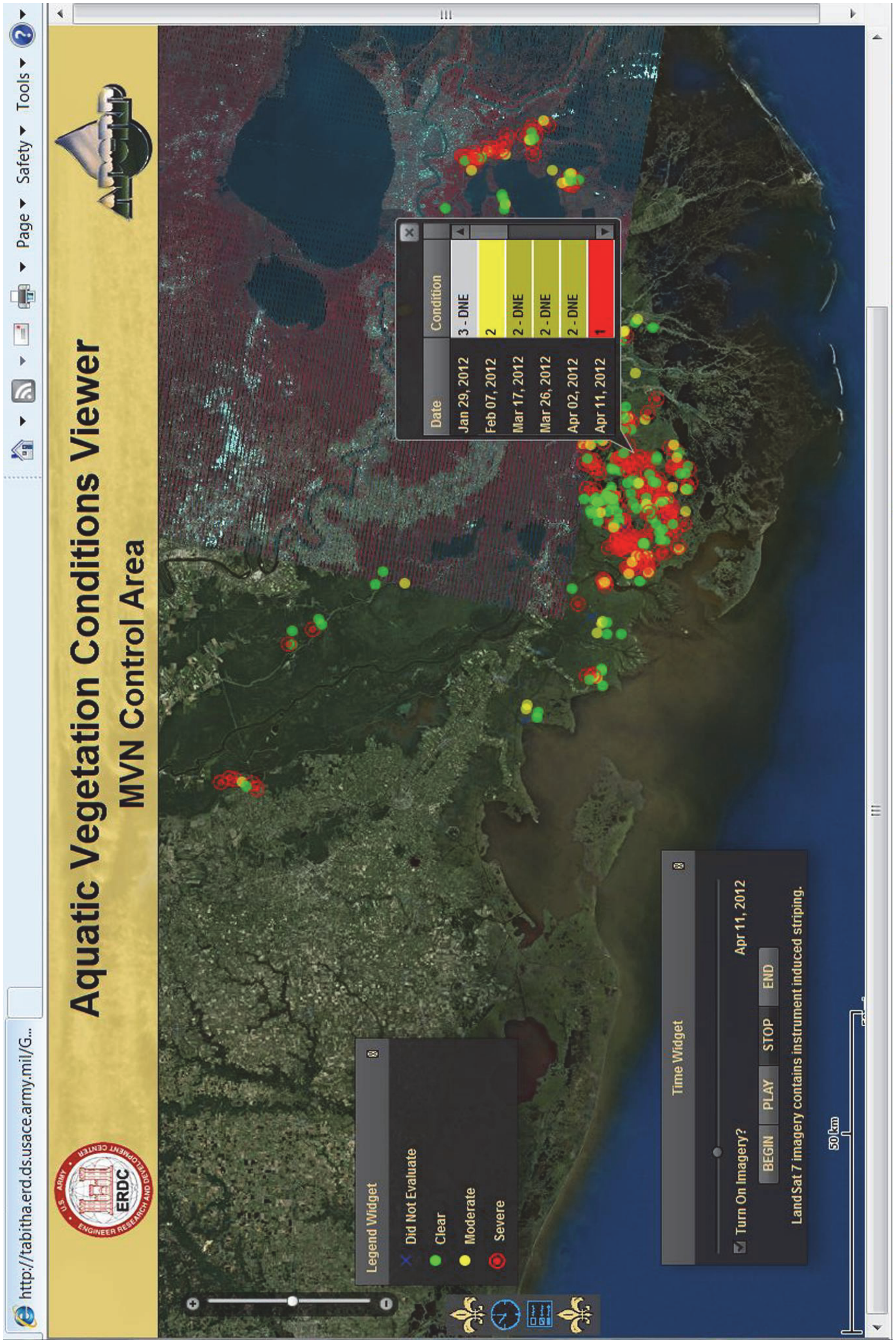

Figure 6. Depiction of the Aquatic Vegetation Conditions Viewer as developed for the MVN RAG Program.

Warmer-than-average temperatures for the 2011-2012 winter season promoted AV survival at many locations in coastal Louisiana. AV problem locations were, however, lowest in the winter and began to increase through the spring and summer (Figure 7). In late June/early July, there was an increase in the number of clear locations. Additionally, the locations that previously contained severe blockages began to experience scattered occurrences of dying floating vegetation. The condition of these blockages may have resulted from treatment by some unidentified third party and/or from increased salt stress associated with higher-than-normal tides due to the occurrence of Tropical Storm Debby in the Gulf of Mexico (Figure 8). The number of blocked locations also declined dramatically after the passage of Hurricane Isaac, which made landfall on 29 August 2012.

Open-water AV mats move with changes in wind and tide. Also, less dense AV populations located in waterways that are strongly affected by tides did move with changing water flow. AV populations located in dead-end canals remained relatively stationary unless they were affected by particularly strong flow (e.g., tropical storm surge).

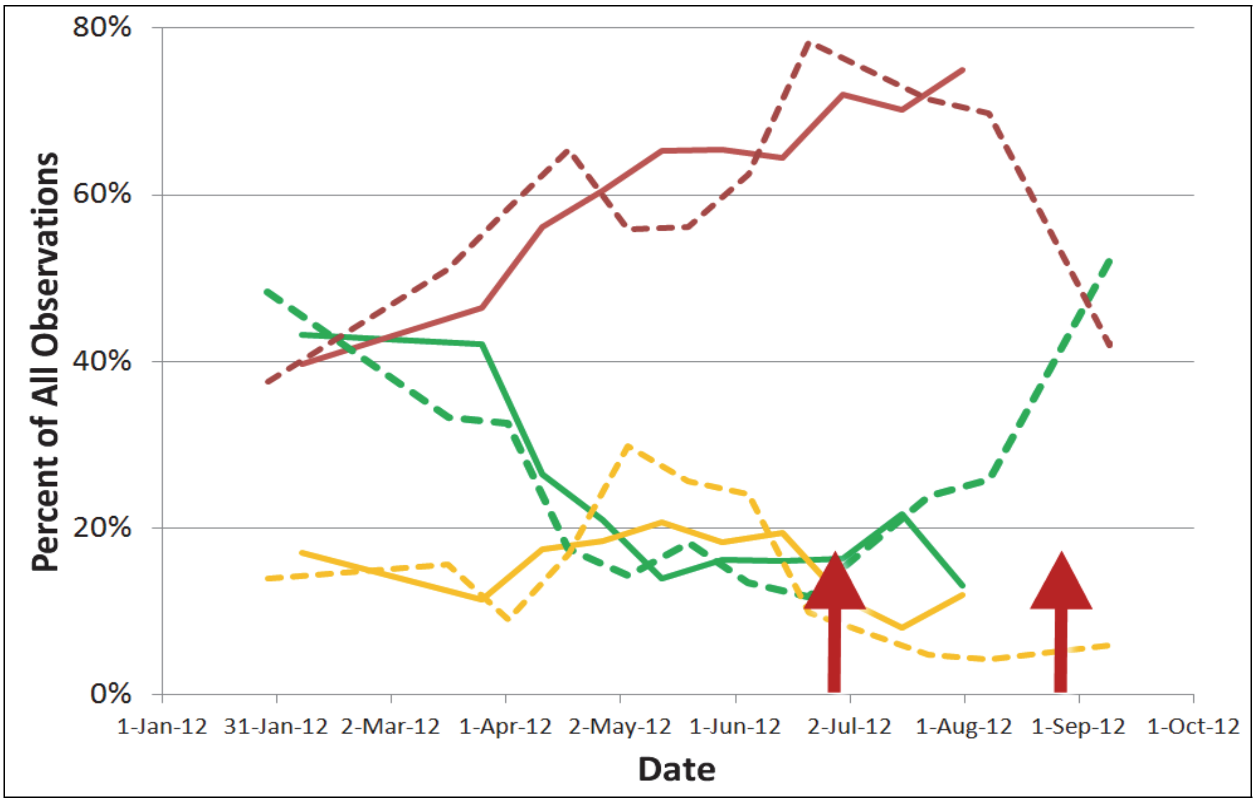

Figure 7. The percentages of all valid observations for each image that were classed as "severe" (red), "moderate" (yellow), or "clear" (green). The solid lines are results based on imagery from Landsat path 22 and the dashed lines are from Landsat path 23. The first red arrow (chronologically) indicates the landfall of Tropical Storm Debby, the second red arrow indicates the landfall of Hurricane Isaac.

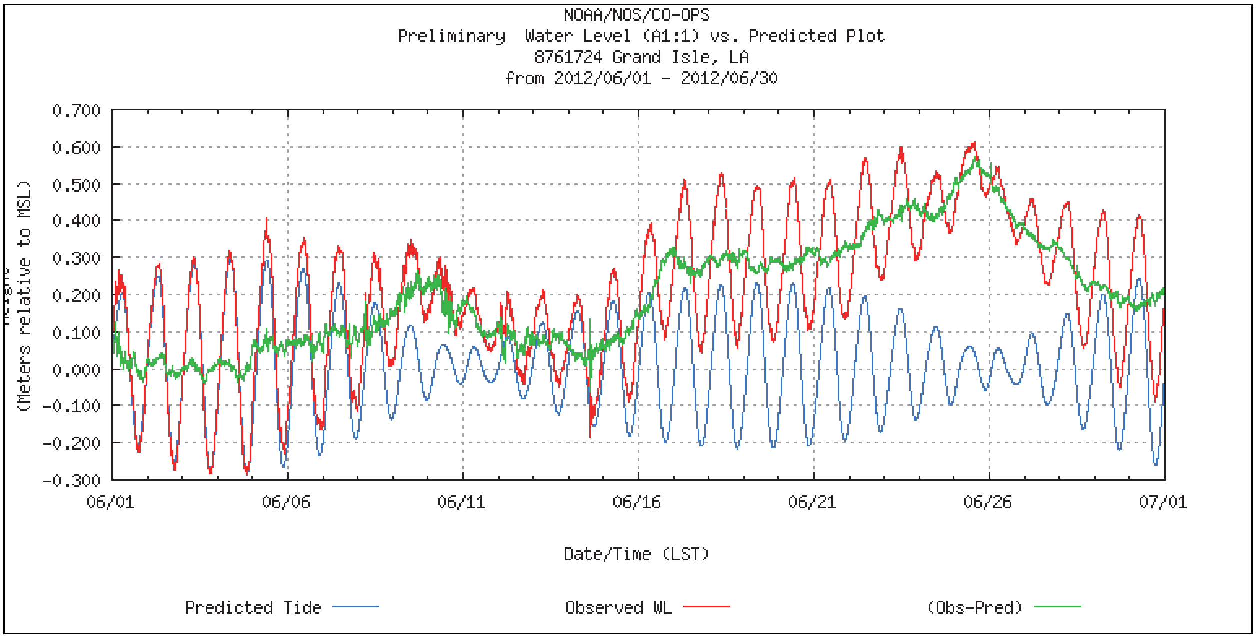

Figure 8. Tidal conditions at the Grand Isle gaging station during June 2012. Due to the presence of Tropical Storm Debby in the Gulf of Mexico in late June, the tidal conditions in coastal Louisiana were well above expected (predicted) tides.

Comparison of Landsat with SPOT 5. Classifications for two Landsat 7 images (24 Jul 2012 and 4 Oct 2012) were compared with results from higher-resolution SPOT 5 (10-m multispectral) imagery collected within 2 days of the Landsat acquisition. The condition was compared for all locations that could be evaluated using both sensors (46 and 64, respectively). Of all sites that were compared using the July Landsat and SPOT 5 images, 91% (42 of 46) received matching classifications. For the October images, there was a 92% (59 of 64 sites) agreement in classification. Most of the misclassifications can be attributed to spatial resolution limitations on the Landsat sensor. For narrow waterways that are 30 m or less in width, the Landsat classification is not reliable. Also, if a larger waterway had AV but still maintained a very narrow passable thalweg, it may have been misclassified as severe (completely blocked) using Landsat. The 10-m multispectral resolution offered by SPOT 5 provides an adequate level of spatial and spectral resolution to accurately identify moderate AV problems (i.e. instances where AV does not completely block the waterway), but the currently low temporal revisit frequency (see below) limited its usefulness for a spatially complete monitoring effort.

Coverage and revisit frequency

Landsat. Landsat 7 does not have Scan Line Corrector (SLC) capabilities. This SLC-off data reduces coverage variably across the image. Coverage is complete for approximately 13 km on either side of the image centerline. The width of striping increases toward the edges of the image and is not consistent from one image to the next. For both paths, striping reduced observations for roughly 20-25% of the locations intersecting the footprint of that path. Cloud cover varied throughout the 2012 period of analysis. Of all Landsat scenes examined, seven scenes (25% of total) were not used to evaluate vegetation conditions because heavy cloud cover obscured the AOR. The 21 remaining images were used to determine AV conditions throughout the year. Scattered cloud cover was highest in late July and early August, obscuring a maximum of 71% of possible locations

on 23 July. Most locations could be evaluated on eight occasions during the 2012 season (29 Jan-9 Sep 2012; Figure 9). If this evaluation frequency (eight times) were spread out equally over the entire time period, this revisit frequency would be once every 28 days. The revisit opportunity ranged from a minimum of 2 to a maximum of 14 of 21 total images.

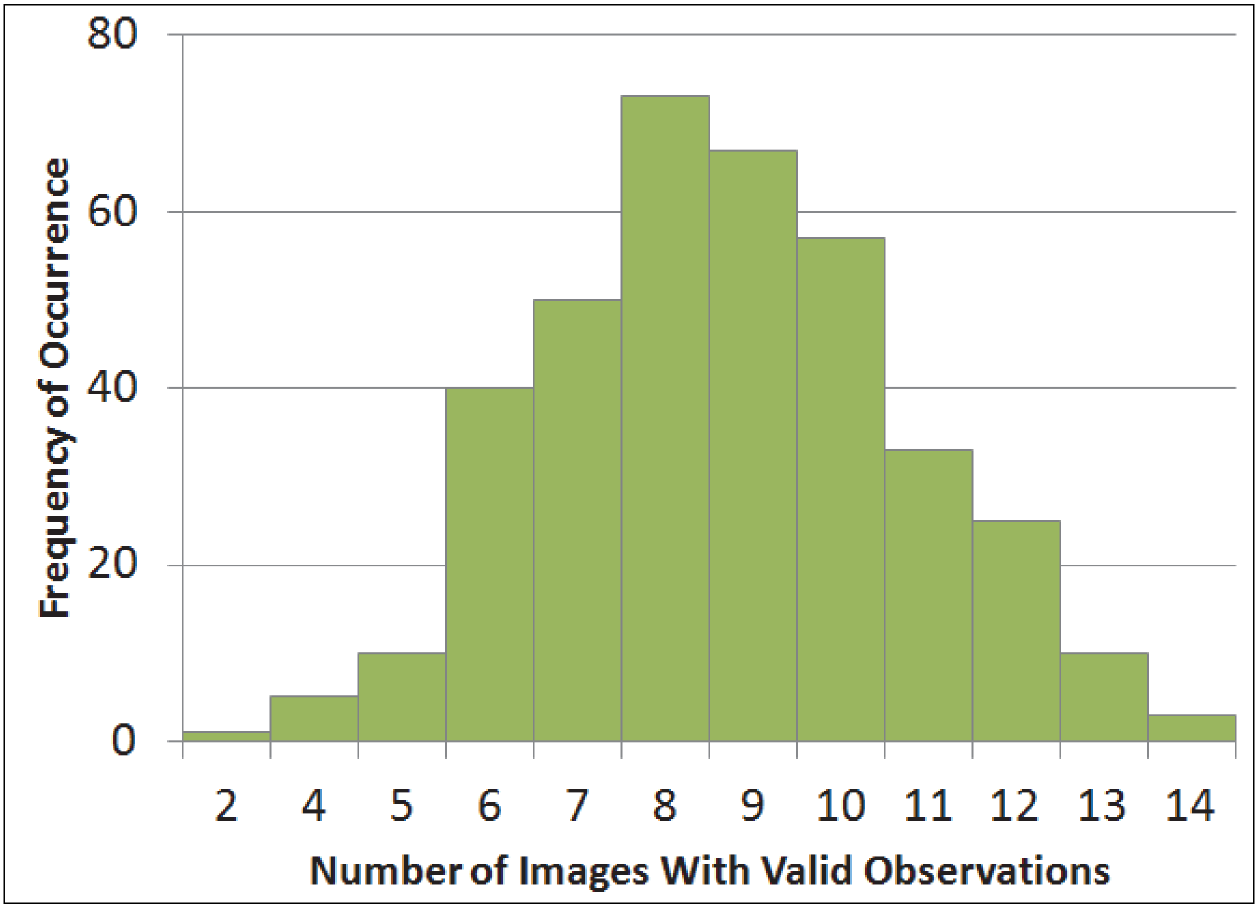

Figure 9. Frequency of occurrence for locations having a given number of revisit observations.

SPOT. Acquisition of imagery over the MVN AOR for SPOT 4 and 5 was generally less frequent compared to Landsat. Both SPOT sensors are taskable, which implies that they should be able to more fully exploit the timing of imagery capture and acquire imagery when cloud conditions are at a minimum. Imagery was, however, rarely acquired under optimal cloud cover conditions. For SPOT imagery, cloud cover was evaluated by dividing the image into eight equal zones and providing a cloud cover percentage for each zone. Typical summer cloud cover in coastal Louisiana is frequently higher over land. As a result, even though reported total cloud cover for a single image may be low to moderate, effective useful coverage may be much more limited for a scene that includes significant amounts of water. Throughout the study period, SPOT 4 imagery products were generally available at monthly or bi-monthly intervals. Cloud cover for these images ranged from clear to 80%, so although not all locations were evaluated using SPOT imagery, revisit frequency at a given location averaged less than once a month. SPOT 5 images were less frequently available—usually achieving less than complete coverage over the MVN AOR during a 3-month time window. The exception was immediately after the passage of Hurricane Isaac when there was repeated coverage over most of the

AOR. The resolution of SPOT 4 did not offer a significant advantage over Landsat, but SPOT 5 resolution was able to more accurately detect moderate infestations compared with Landsat.

High-resolution sensors. Imagery from other high-resolution sensors was available only sporadically. Attempts were made to task high-resolution sensors to acquire new imagery through existing no-cost agreements, but these efforts were largely unsuccessful. The reasons for this difficulty were unclear, but were probably related to competing sensor tasking priorities from other federal agencies. Imagery was more readily available through direct purchasing requests made to the vendors. High-resolution, four-band imagery was purchased in the fall of 2012 to assess AV conditions at seven "hotspot" areas defined by MVN field crews. Complete one-time coverage over the entire MVN AOR would have required purchase of approximately 45 scenes for a total cost of $81,000 (at the time of writing). Additionally, direct purchase of the WV-2 eight-band imagery would have been more expensive than obtaining four-band imagery.

Comparison with high-resolution imagery (Figure 10) confirmed that moderate-resolution sensors such as Landsat imagery provide suitable spatial resolution to detect large AV problem areas that completely block a waterway, but that detection of less dense populations is not as reliable. Evaluation of moderate and lightly fringing populations of AV conditions was easily accomplished through visual examination of high-resolution imagery captured using the Quickbird, GeoEye, and WorldView-2 sensors. Although the presence of AV was readily apparent through visual examination of the high-resolution imagery, using a supervised classification of that imagery to locate AV was accomplished with only variable success. Variation in AV species, density, and stages of growth and senescence results in a large diversity of spectral characteristics. Errors made in classifying floating AV included assigning similar spectral signatures to adjacent marsh habitats, and omitting obvious areas of AV infestation whose spectral signature differed slightly from the training data. Visual examination, coupled with spatially and temporally coordinated ground truth photography, proved to be the best method for establishing a reliable relationship between high-resolution imagery and ground conditions. Resampling of high-resolution (2 m or less) imagery showed that fringing populations of water hyacinth could be equally well detected at 5-m resolution (Figure 11). Further resampling to 10 m showed that fringing populations could also be detected at this coarse resolution, but that discrimination was much more difficult.

CONCLUSIONS

Sensor evaluation and recommendation. Depending on the desired update frequency and desired minimum spatial resolution, an effective AV monitoring program is possible using remotely sensed imagery. Remote sensing offers a safe, comprehensive, and objective means of identifying and tracking problems associated with AV compared with traditional field assessment methodologies. This study demonstrated one possible monitoring configuration that relies primarily on Landsat and other no-cost imagery to deliver broad-scale assessments of significant problem areas. Landsat imagery provided repeat, moderate-resolution coverage of the MVN AOR. It was shown that most locations within this AOR could be observed an average of once every 4 weeks. This sensor platform was very effective for monitoring large accumulations of AV on larger waterways and lakes whose minimum dimension is not less than 30 m, but there are significant limitations if the goal is to monitor lower-density AV populations or very narrow waterways. Imagery available from other sensors could also be incorporated into condition assessments on an ad hoc basis as imagery becomes available. The launch

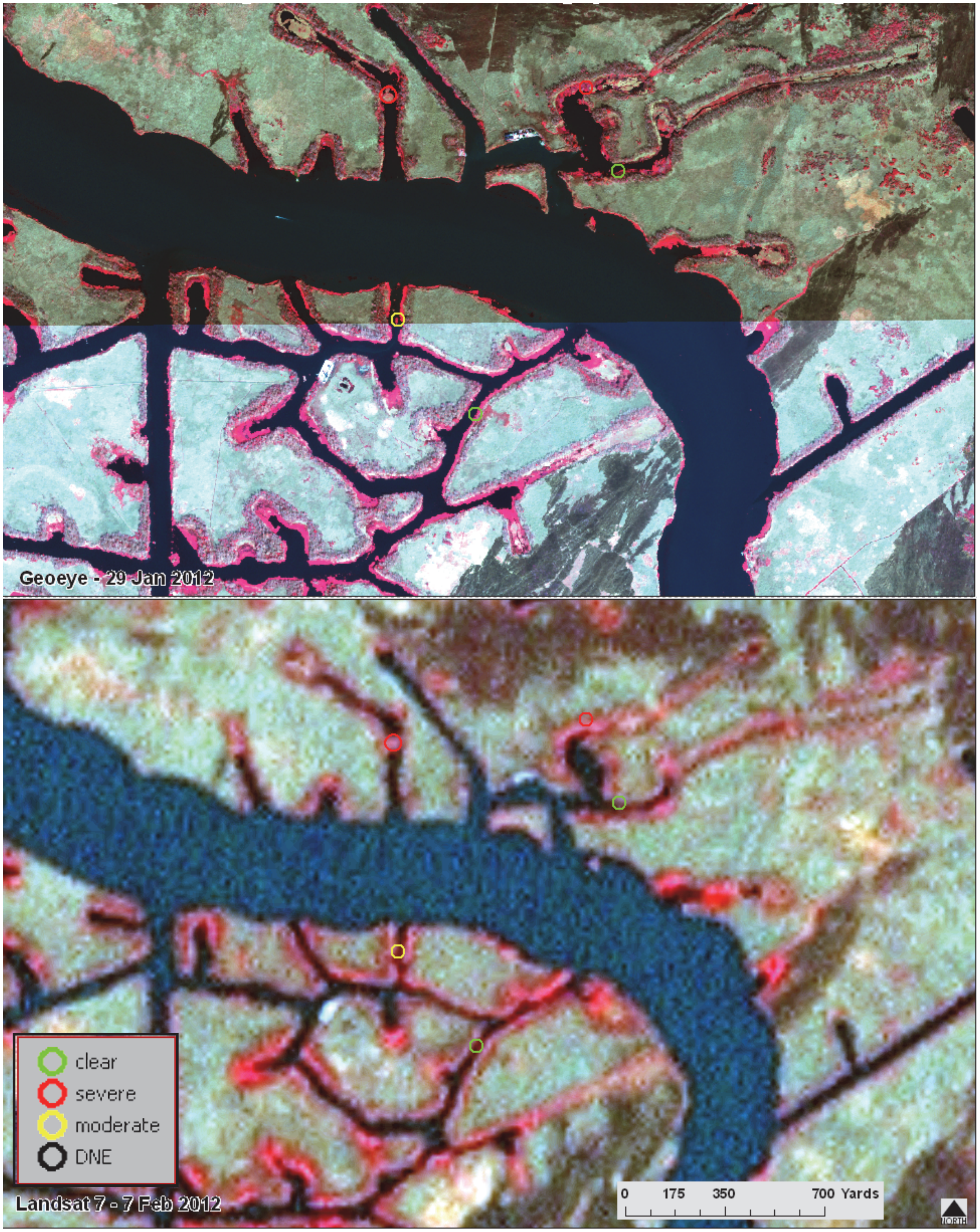

Figure 10. Comparison of imagery on similar dates from high-resolution (GeoEye-1; 29 Jan 2012; upper panel) and moderate-resolution (Landsat 7; 7 Feb 2012; lower panel) imagery. Circles denote classification of condition based on Landsat imagery alone.

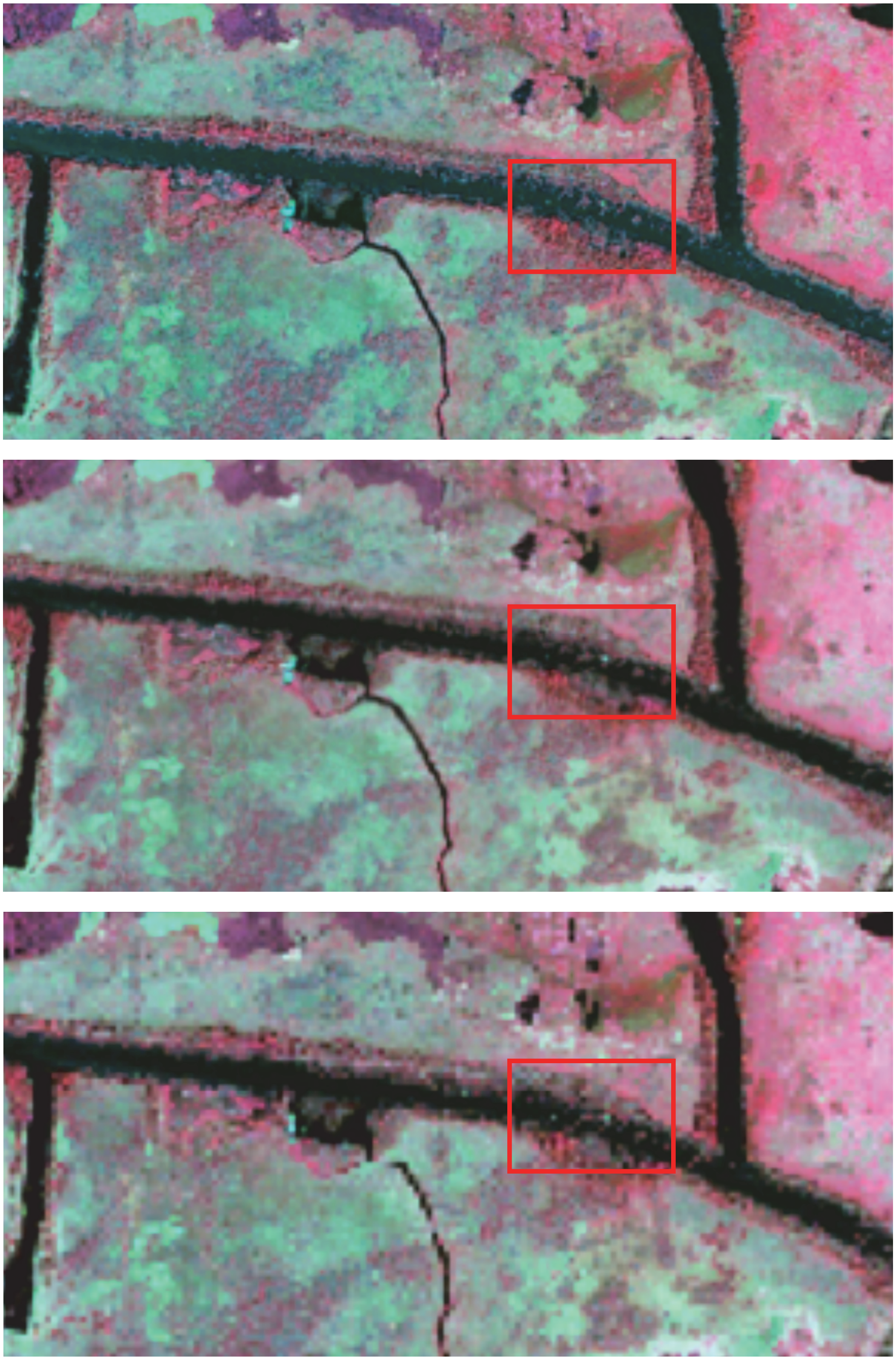

Figure 11. Quickbird imagery captured on 3 Oct 2012. Upper panel shows full-resolution (2-m) imagery. Fringing patches of water hyacinth may be seen in the main canal running NW-SE. Middle panel is the same image resampled to 5 m. Lower panel is resampled to 10 m.

of Landsat 8 in February 2013 resulted in even greater opportunities to monitor AV conditions at this scale. Overflight revisits (including already overlapped areas) will double, coverage will be complete with no striping, and imagery access will remain free.

If higher resolution is required, SPOT 5 imagery may be best used to achieve more detail while still retaining a relatively large spatial footprint. Though SPOT 4 imagery does potentially provide increased resolution (10-m panchromatic and 20-m multispectral) over Landsat, the SPOT 4 imagery was not always provided with the higher-resolution panchromatic band. Multispectral imagery from SPOT 5 offers improved delineation of moderate-density AV in narrow bayous and waterways without a significant decrease in spatial footprint, and the spatial resolution of the product may be further increased if the panchromatic band is available. Indications are that increased priority of SPOT 5 imagery acquisition over coastal Louisiana may be possible with some cost-share agreements with the USGS NADB Program. It is unknown, however, if the NADB Program could provide the agility of response to tasking requests that may be required to support an AV monitoring effort.

In this study, obtaining imagery from the highest-resolution sensor platforms was a significant challenge. The accuracy and detail provided by high-resolution imagery (2-5 m) offers the best alternative to the traditional field-crew-based assessment of AV conditions. However, current hurdles to no-cost imagery acquisition through AGC and the high cost of direct acquisition through the vendor could restrict the use of high-resolution imagery in monitoring ground conditions.

Future research opportunities. Previous studies have shown the ability to classify a variety of aquatic vegetation species using satellite imagery (Jakubauskas et al. 2002, Everitt et al. 2007, Silva et al. 2008). Preliminary inspection of Landsat imagery indicated that it should be possible to establish not only the presence and absence information for AV (as was done in this study), but also to identify detailed spectral signatures for various species or species groups of AV. Water hyacinth was the dominant species of concern for the MVN AOR, but throughout Louisiana's waterways, dense populations of other species also impede navigation and access. Hydrilla (*Hydrilla verticillata*) and American lotus (*Nelumbo lutea*) in and near the Atchafalaya basin show distinct spectral and spatial patterns based on recent Landsat imagery (Figure 12). Giant salvinia (*Salvinia molesta*) and Cuban bulrush (*Oxycaryum cubense)* populations are both expanding in south Louisiana and it may be possible to use the historical library of Landsat imagery to determine the patterns and rates of expansion. Though four-band sensors may adequately distinguish some aquatic plant species (e.g. giant salvinia, Everitt et al. 2007), more detailed species may require additional bands (e.g. WV-2 or hyperspectral imagery).

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Figure 12. Example of hydrilla dominance in shallow open-water areas of Lake Henderson (left) and American lotus dominance in Lake Fausse Point (right). Imagery is Landsat 7 captured on 11 Oct 2012.

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REFERENCES

Everitt, J. H., R. S. Fletcher, H. S. Elder, and C. Yang. 2007. Mapping giant Salvinia with satellite imagery and image analysis. *Environ Monit Assess* 139(1-3):35-40.

Jakubauskas, M. E., D. L. Peterson, S. W. Campbell, F. deNoyelles, Jr., S. D. Campbell, and D. Penny. 2002. Mapping and monitoring invasive aquatic plant obstructions in navigable waterways using satellite multispectral imagery. In *ISPRS Future Intelligent Earth Observing Satellites 2002 Conference Proceedings.*

Jensen, J. R., S. Narumalani, O. Weatherbee, and H. E. Mackey, Jr. 1992. Measurement of seasonal and yearly aquatic macrophyte changes in a reservoir using multidate SPOT panchromatic data. In *Technical Papers, American Society for Photogrammetry and Remote Sensing* 1:167-176. Bethesda, MD.

Silva, T. S. F., M. P. F. Costa, J. M. Melack, and E. M. L. M. Novo. 2008. Remote sensing of aquatic vegetation: Theory and applications. *Environ Monit Assess* (2008) 140:131–145.

Steeves, P. A., M. C. Waldron, and J. T. Finn. 1999. Aquatic macrophyte mapping using Thematic Mapper imagery and a geographic information system. *1999 ESRI Users Conference, San Diego, CA, July 26-30, 1999.*

US Department of the Army. 2001. *Climatic, hydrological, and topographic services - Geospatial information and services.* Army Regulation 115–11. Washington, DC. *http://www.apd.army.mil/pdffiles/r115_11.pdf*